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Dynamic response and liquefaction analysis of seabed-rubble mound breakwater system under waves

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ABSTRACT

Dynamic response and liquefaction potential of granular seabed around a rubble mound breakwater is investigated under waves. Dynamic response of the system is assumed to be governed by coupled Biot equations of poroelasticity. Mathematical formulations in terms of governing equations of partially-dynamic and quasi-static cases are considered. Dynamic response of seabed soil is analyzed using classical finite elements and a number of parametric studies are performed to draw a complete picture of the response of the system. Vertical displacement, shear stress and pore water pressure distributions are considered as the most representative variables defining the variations of response of the whole system and which are thus evaluated along some key cross sections around the breakwater. The results indicate that inertial terms associated with solid skeleton have almost no effect on the dynamic response and liquefaction potential. It was found that large amount of wave-induced shear stresses are taken by a relatively rigid core layer contributing to the breakwater stability where also the pore pressures dissipate significantly towards the seabed interface. Standing wave-induced instability of the system is also investigated in terms of instantaneous liquefaction based on the effective mean stress criterion. There is liquefaction observed at the seaward surface of the rubble whose depth increases significantly with decreasing saturation. While the core overall provides more stability, the adverse effect of this is more liquefaction in the outer layer.

1. Introduction

Marine infrastructure plays a vital role in relation to energy, environment and sustainable development. Coastal and offshore structures built to protect coastal regions constitute a significant part of marine infrastructure. The instability of such coastal structures is induced primarily by the action of oscillatory and impact forces caused by wave storms and strong ocean currents. Geotechnical aspects play a significant role in the initiation of these instabilities. Thus, the evaluation of wave-induced response of seabed around structure-foundation systems plays a key role in mitigation of the associated hazard. In this study, dynamic response and instability of a rubble mound breakwater (RMB) - seabed system are investigated. Instantaneous liquefaction of seabed around the rubble is evaluated based on the mean effective stress criterion.

Analysis of breakwater-seabed system as a whole requires accurate modeling of soil dynamic response under cyclic wave action. Poroelasticity theory [1,2] has the most fundamental and mathematically sound background for numerical modeling of saturated porous granular soil under dynamic loads. Thus, it is employed in solving for the internal forces, deformations and pore pressure developments inside the porous structure of the system in coastal geotechnical engineering. Variation of these field variables in temporal and spatial domains determines whether the system sustains its structural integrity under critical wave storms. Hence a stability condition called 'instantaneous liquefaction' where soil loses its mean effective interparticular stress at any time instant when the wave pressure is exerted on the surface of the seabed soil (particularly under the wave trough), is analyzed considering some air voids being present in the medium. To the best of our knowledge, this has not been comprehensively analyzed through the poroelasticity theory before.

A number of numerical studies have been conducted so far to understand the stability conditions of RMB under wave action. Mase et al. [3] studied the quasi-static response of a RMB for two cases of rubble under standing waves; one with a core and another without a core. In a research study by Mizumura [4], an analysis of wave-induced current in a RMB is presented. Van Gent [5] studied the wave interaction with berm breakwaters by means of physical and numerical models. Physical

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Table 1
Numerical values of the parameters used in 2-D free field analysis.

Parameter	Symbol	Unit	Value
Depth of seabed	h	m	7
Elasticity modulus of soil	E	kN/m^2	13500
Poisson's ratio	ν	–	0.3
Permeability	$k_z = k_x = k_s$	m/s	0.001
Bulk modulus of pore water	K_f	kN/m^2	2.3×10^6
Saturation	S_r	–	1
Porosity	n	–	0.35
Unit weight of soil	γ_s	t/m^3	2
Unit weight of water	γ_w	t/m^3	1
Gravitational acceleration	g	m/s^2	9.81
Wave height	H	m	0.049
Wave length	L	m	7
Water depth	d	m	7
Period	T	s	1

model tests verify the wave motion calculated by the numerical model. Seismic response of rubble-breakwaters was studied by Memos et al. [6], Ye and Jeng [7] and Ulker [8]. Matsuda et al. [9]. examined the stability of concrete armor blocks covering the rubble mound of a composite breakwater in a two dimensional (2-D) model test. Zhao et al. [10] presented loosely deposited foundation behavior around a composite breakwater subject to ocean wave impact. Zhao et al. [11] presented the numerical study of wave-induced soil response in a sloping seabed in the vicinity of a breakwater. Finally, Ye et al. [12] investigated wave-induced dynamic response of poro-elastoplastic seabed foundations and a composite breakwater. Also a number of studies have investigated fluid–structure–seabed interactions Ye et al. [13,14].

A new method to calculate the necessary mass of armor blocks for the breakwater in which the impact of breaking waves is taken into account, is proposed. Lin and Liu [15] presented the numerical study of breaking waves in the surf zone. Losada et al. [16] numerically studied the wave overtopping of RMBs. Jeng et al. [17] and Ulker et al. [18] used finite element method (FEM) to analyze the response of seabed and rubble mound foundation around a vertical breakwater under pulsating loads. Ulker et al. [19] modeled the dynamic response and instability of the same system under breaking waves. In these analyses breakwater model was assumed to be a porous medium as well. Lately, Cihan and Yuksel [20] studied the behavior of different types of armor units of RMB under cyclic loading.

This paper looks into the stability and dynamic response of RMBs from their foundations standpoint. That is, the stability of seabed is largely responsible for the mechanism of failure of RMB under surface waves. Besides, the likelihood of liquefaction of granular seabed is the driving factor causing such failures. Hence, the instantaneous liquefaction of soil under standing waves is studied through finite elements.

2. Dynamic analysis of seabed response

2.1. Mathematical formulation

Dynamic analysis of seabed is governed mathematically by poroelasticity equations essentially taking into consideration the linear momentum balances of two phases (solid and pore fluid, mostly water) along with the mass conservation of pore water during flow. The viscous drag force applied due to flow through porous medium in terms of D'Arcy's law which is linearly proportional to the hydraulic gradient, is also included in the equations. Thus, the momentum balance of the total system is written as:

$$\sigma_{ij,j} + \rho g_i = \rho_f \ddot{\overline{w}}_i + \rho \ddot{u}_i \tag{1}$$

where the first term on the left is the divergence of total stress, the second is the body force, and the right hand side terms are the inertias of relative pore water motion ($\ddot{w}$) and the motion associated with soil grains ($\ddot{u}$), respectively. The momentum balance of the pore water leading to its equilibrium is:

$$-p_{,i} + \rho_f g_i - \frac{\dot{\overline{w}}_i}{k_i}\rho_f g_i - \rho_f \ddot{u}_i - \frac{\rho_f}{n}\ddot{\overline{w}}_i = 0 \tag{2}$$

where the first term is the gradient of pore pressure (p), second is the body force, third is the drag force from the D'Arcy's law, the forth is the inertial term of the solid part in relation to pore water flow and the last term is the inertia of the pore water itself. In Eq. (2) k_i is the permeability and n is the porosity. Finally, the law of conservation of fluid

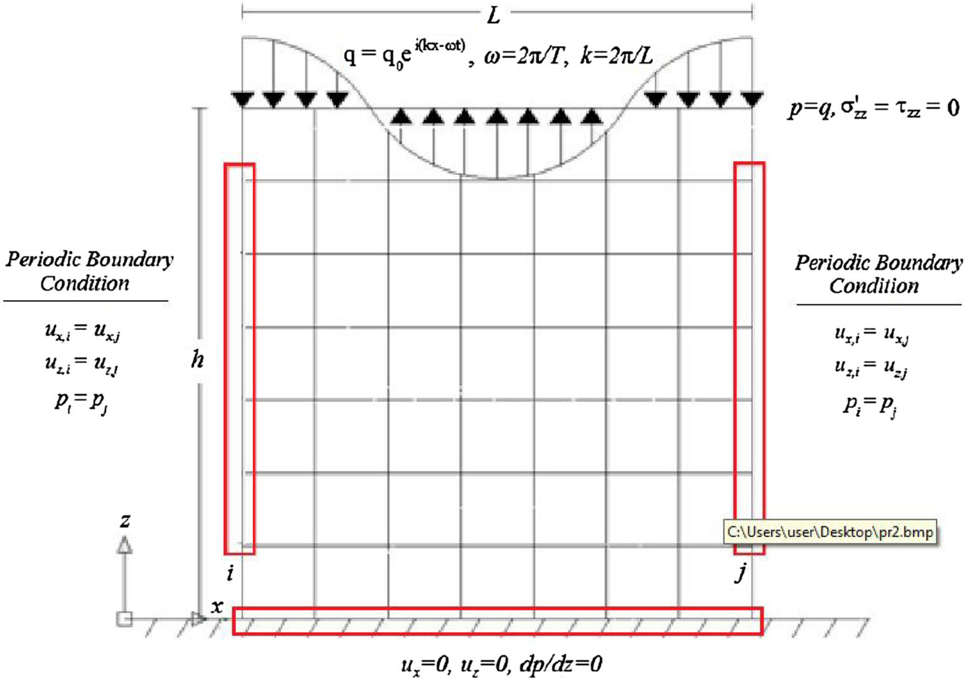

Fig. 1. A layer of saturated porous seabed under progressive wave loading [27].